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The CEBAF Large Acceptance Spectrometer

- Highlights of the Physics Program -

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Highlights of the Initial CLAS Physics Program

I. Introduction

The thrust of the experimental program at CEBAF may be stated as follows: Given QCD as the theory of the strong interaction, in what way are nucleons and nuclei made up of quarks and gluons? Electromagnetic probes such as photons and electrons, are powerful tools to probe the internal structure of nucleons, other light baryons, and light nuclei. This is because the electromagnetic interaction is well understood: it interacts in a point-like manner with hadronic matter, and the spatial resolution of the probe can be adjusted by changing the four-momentum transfer (Q^2), allowing to map the interior of the object (nucleon, nucleus) being studied. The experimental program already approved for CLAS will make important contributions to the study of the quark and gluon structure of nucleons and nuclei as well as to probing the limits of conventional nuclear theory. Combining the large acceptance of CLAS with the quality of the CEBAF beam, these measurements can be done with unprecedented precision and completeness.

The fundamental building blocks of nuclei are the nucleons. The detailed understanding of the nucleon in terms of its substructures is of utmost importance for the understanding of more complex systems such as light nuclei. In the CLAS program, the quark and gluon structure of the nucleon will be studied by mapping out its spatial and spin structure. This will be accomplished by measurements of the excited spectrum of light baryons and their electromagnetic transition form factors, and measurement of the spin structure functions of the proton in the non-perturbative regime of the strong interaction force, where much of the spin structure of the proton is expected to reside.

In the following we will discuss examples of the experimental program in CLAS that are of importance for this program.

II. The Structure of the Nucleon

The N^* program will study interactions of electrons and photons with hydrogen and deuterium targets. It will address a number of specific goals pertaining to the quark and gluon structure of the proton and neutron. For this program, complete solid angle coverage is very important since detailed partial wave analyses of the various processes in single or multiple meson production are necessary in order to identify the quantum numbers of the excited states.

Search for "Missing" 3-Quark States

Experiment 91-24 involves a search for excited nucleon states which are predicted in the QCD extended quark model, but have not been observed in well studied hadronic reactions like $\pi N \rightarrow \pi N$ scattering. The existence or non-existence of these states is crucial in determining the symmetry structure underlying the light-quark baryon spectrum. These states are predicted in the $SU(6) \otimes O(3)$ symmetric model, but they are absent in the quark cluster model, where the three valence quarks form a diquark-quark configuration, which has fewer degrees of freedom than the symmetric model. For example, the symmetric quark model predicts the $F_{15}(1950)$ state to exist, and to decay into a proton and an ω meson, whereas this state has no place in the quark cluster model. The experiment will measure the reaction

$$ep \rightarrow e'p\omega$$

$$\rightarrow \pi^+\pi^-\pi^0$$

to search for this state. Figure 1 shows the expected statistical precision and angular coverage. Complete angular coverage is extremely important in order to disentangle the various contributions to the cross section. In particular, large angle ω production will be sensitive to the resonance contribution.

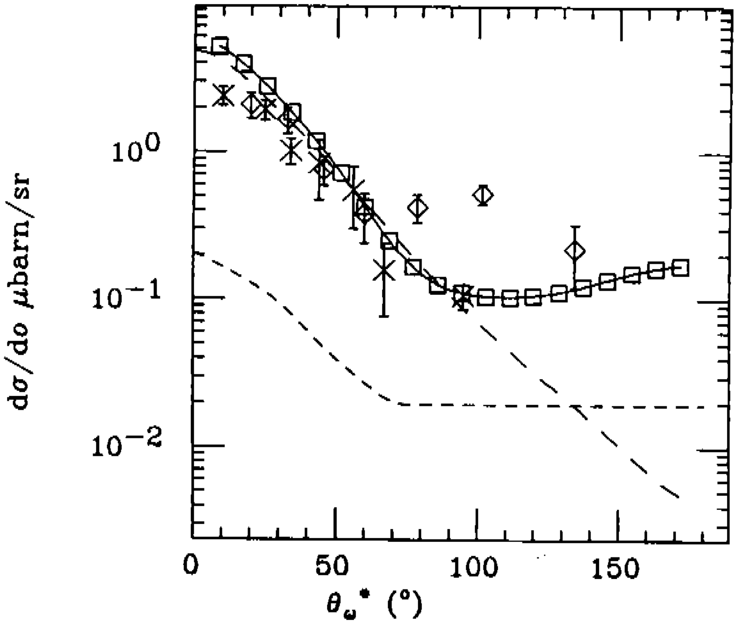

Figure 1: Cross section for $\gamma_v p \rightarrow p\omega$. The open squares are the data expected for a specific model prediction. The deviations from the long dashed line are due to resonance production.

Gluonic Degrees of Freedom

Experiments 89-37, 89-42, and 91-02 will study the role of gluonic degrees of freedom in the interaction between the three quarks confined in a nucleon. Gluon exchange is, for example, expected to generate the color magnetic hyperfine force which breaks the spherical symmetry of the $\Delta(1232)$. This spin-spin force is predicted to have a very strong impact on the entire spectrum of light-quark baryons. Accurate information about the strength of this interaction will therefore be very important. In these experiments the effect of the color hyperfine force will be studied for the transition to the $\Delta(1232)$ which is well isolated from other resonant states and can thus be studied under well defined conditions. Experiments 89-37/-42 will measure the ratio of electric quadrupole E_{1+} and magnetic dipole M_{1+} transition strength with high precision, over a large range in the four-momentum transfer (Q^2). Different models of the nucleon structure give significantly different predictions for the Q^2 dependence. We expect, that by the time the experiment will be carried out, predictions from QCD lattice calculations over a larger Q^2 range and with higher accuracy can be confronted with the data. Figure 2 shows the existing data in comparison with theoretical predictions, and the error bars expected from the experiment 89-37/42. Restoration of chiral invariance requires that $E_{1+}/M_{1+} \to 1$ at very high Q^2. The transition from the non-perturbative regime to the regime where pertubative QCD methods can be applied will be explored in experiment 91-02.

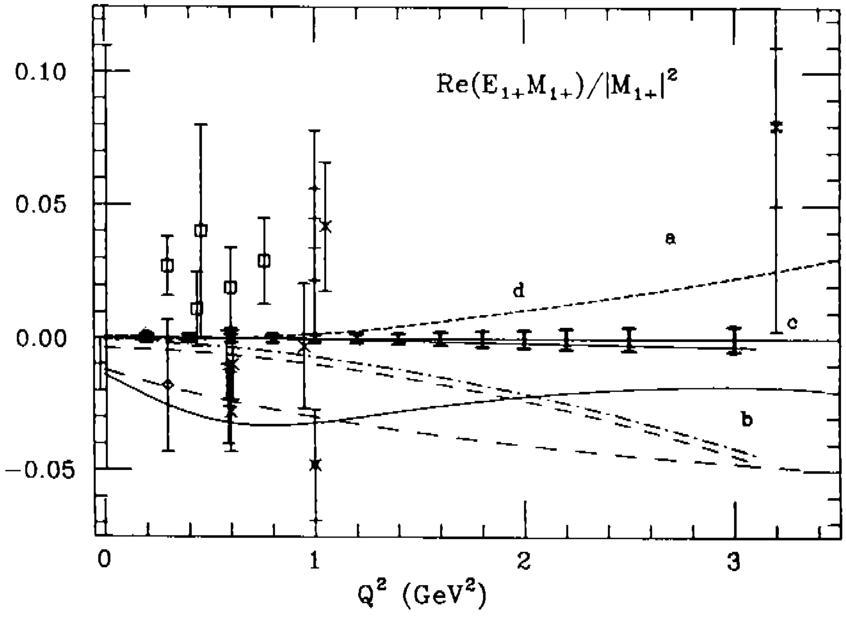

Figure 2: E_{1+}/M_{1+} for $\Delta(1232)$ excitation. Existing data and expected statistical error bars in experiment 89-37.

Search for Hybrid Baryons

The role of explicit gluonic degrees of freedom in the baryon spectrum is one of the topics of experiment 89-38. In hadronic production, gluonic excitations with three quarks and one valence gluon cannot be distinguished from regular 3-quark states with the same quantum numbers. In electron, scattering they can be identified because of their distinctively different electromagnetic transition form factors.

The Roper resonance presents a serious problem for the non-relativistic quark model. The state is associated with a radially excited state of zero orbital angular momentum. However, the low mass is not understood in the quark model, and the predicted transition form factors are in disagreement with the data. This experiment will measure the transition form factor of the Roper resonance to determine whether it is a radial excitation of a 3-quark state, or the gluonic partner of the nucleon, as has been suggested in recent theoretical models. Figure 3 shows existing data with theoretical calculations treating the Roper state as a radially excited 3-quark state, or a gluonic excitation of the nucleon. Although the hybrid model gives better agreement, much improved data will be needed before definite conclusions can be drawn about the nature of this state.

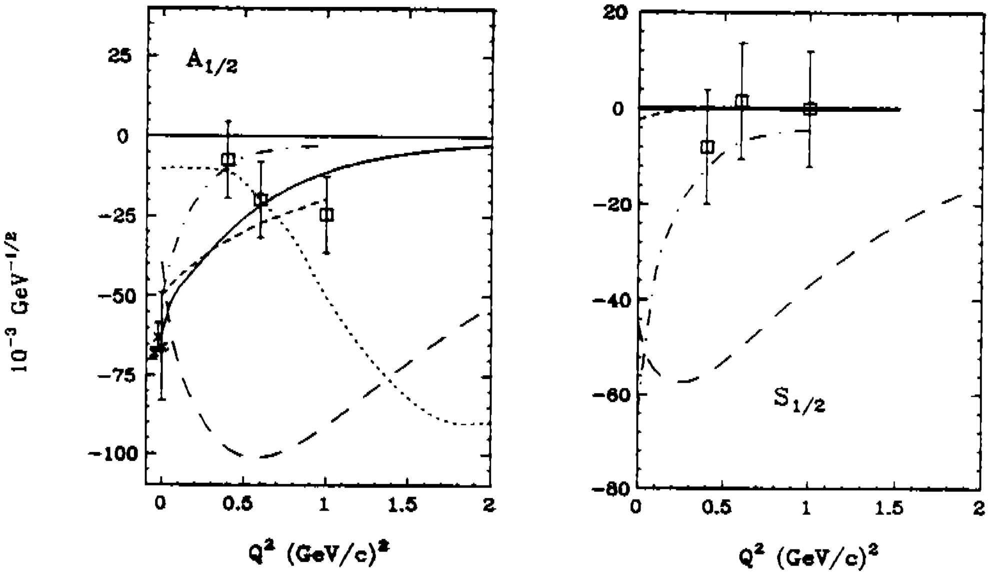

Figure 3: The transverse (left) and scalar transition form factors of the Roper resonance. Long dashed lines are the non-relativistic quark model, dotted lines the relativistic quark model, and solid lines the hybrid model. Open squares, and the short-dashed and dash-dotted lines indicate results of experimental analyses.

Precise tests of the constituent quark model

The range of validity of dynamical quark models and the possible onset of perturbative QCD will be examined in experiments 89-38, 89-39, and 91-08, both with photons and in electron scattering, in a wide range of Q^2. These experiments will measure the reactions $p(e,e'p)\pi^0$, $p(e,e'\pi^+)n$, $p(e,e'p)\eta$, and $p(\gamma,p)\eta$, and determine the transition form factors of the $S_{11}(1535)$, $D_{13}(1520)$ as well as those of many other resonances. The form factor ratio of these two states can be predicted by relativistic quark models with little theoretical uncertainty. Precise measurement of this ratio as a function of Q^2 will therefore provide stringent tests of the range of validity of the quark model. Figure 4 shows the data from previous experiments. The highest Q^2 values may signal a breakdown of the constituent quark model, which can be studied with the much improved data expected from the CLAS experiments. Measurement of states such as $S_{31}(1620)$ and $D_{33}(1700)$ will allow stringent tests of the single quark transition assumptions often used in calculation of the transition form factors.

Experiment 91-02 extends these measurements to higher Q^2 values, where the transition to the perturbative QCD regime may take place, and the form factors are predicted to assume a simple power law fall-off. Data from inclusive electron scattering experiments are consistent with the transition taking place at $Q^2 = 4 - 5\ GeV^2$.

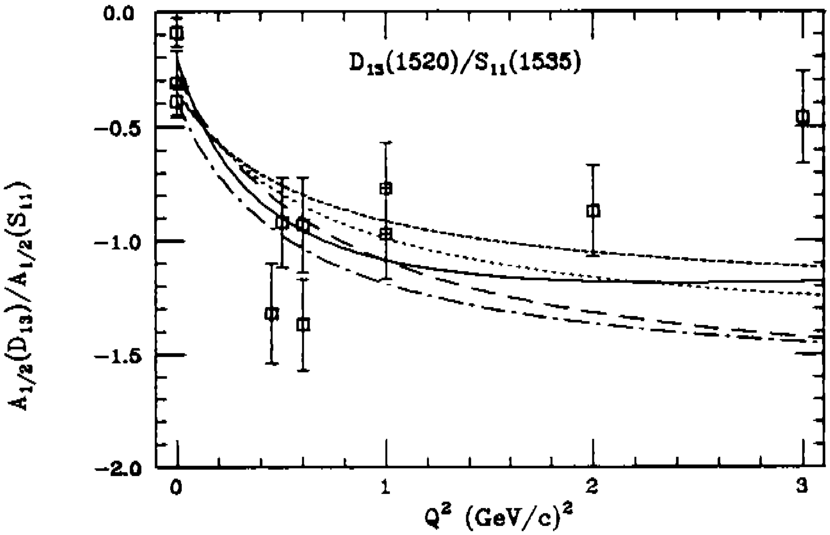

Figure 4: The ratio of $D_{13}(1520)$ and $S_{11}(1535)$ transition form factors, with predictions from non-relativistic and relativistic quark model calculations.

III. Spin Structure of the Proton

In deep inelastic scattering, measurement of the polarized structure function $g_1(x, Q^2)$ led to the conclusion that only a small part of the proton spin is carried by the quarks. A possible consequence is that much of the strength in the spin structure functions is the result of orbital angular momentum excitations of the 3-quark system. These contributions are genuinely non-perturbative and cannot be measured in deep inelastic scattering. A large fraction of these contributions are likely to come from the nucleon resonance region which can be measured at CEBAF energies.

Extended Gerasimov-Drell-Hearn Sum Rule

Experiments 91-15 and 91-23 will measure contributions of the resonance region to the spin structure functions of the proton. Experiment 91-15 will determine the single meson contributions to the Gerasimov-Drell-Hearn sum rule by measuring the spin asymmetry $A_1(\nu, Q^2 = 0)$ for the reactions $\vec{p}(\vec{\gamma}, p)\pi^0, \eta$, and $\vec{p}(\vec{\gamma}, \pi^+)n$, with the goal of establishing the $Q^2 = 0$ limit of this fundamental sum rule. Experiment 91-23 will measure the two spin structure functions $A_1(\nu, Q^2)$ and $A_2(\nu, Q^2)$ as a function of ν and Q^2 by measuring inclusive polarized electron scattering from a polarized proton target $\vec{p}(\vec{e}, e')$. Figure 5 shows the expected error bars for $A_1(\nu, Q^2)$ compared to previous measurements and to theoretical calculations. Knowledge of $A_1(\nu, Q^2)$ in a large kinematical range will allow determination of the Q^2 evolution of the Gerasimov-Drell-Hearn sum rule in the transition from the confinement regime to scaling.

Low energy QCD makes predictions about the low Q^2 behavior of this sum rule. Extrapolations of the deep inelastic behaviour to lower Q^2 are in disagreement with expectations from resonance contributions. These predictions will be put to a serious test by this experiment. Figure 6 shows the expected error bars from this experiment in comparison with theoretical models. Obviously, the experiment will make an important contribution towards clarifying the proton spin structure in the nucleon resonance region.

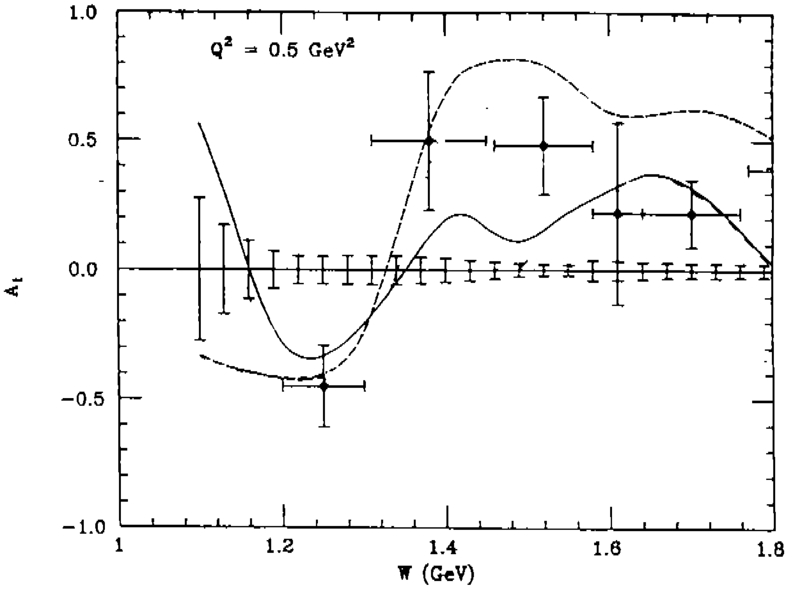

Figure 5: Spin structure function A_1 at fixed $Q^2 = 0.5$ versus the invariant hadronic mass W. Data points are from a SLAC experiment. The error bars around $A_1 = 0$ are projections for experiment 91-23.

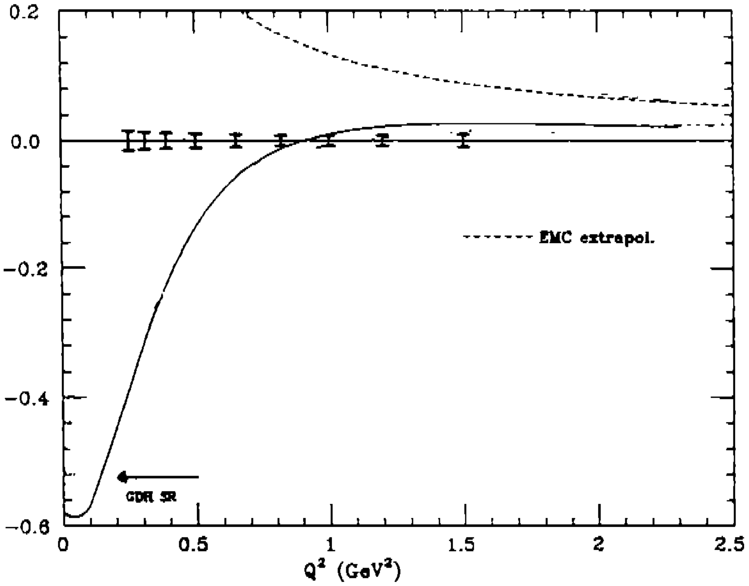

Figure 6: Q^2 dependence of the Gerasimov-Drell-Hearn sum rule in various models. The error bars show the expected accuracy of experiment 91-23.

IV. Strangeness production

Associated strangeness production in $\gamma p \rightarrow K^+Y$, where Y represents a ground state or excited state hyperon $(\Lambda, \Sigma, \Lambda(1405), \Sigma(1385)$, or $\Lambda(1520)$, will be studied in experiment 89-04 and 89-24. Radiative transitions of several excited hyperon states will be measured in 89-24, such as:

$$\begin{aligned} \Lambda(1520) &\rightarrow \Sigma^0(1193) + \gamma \\ &\qquad\qquad \rightarrow \Lambda + \gamma \\ &\qquad\qquad\qquad\quad \rightarrow \pi^- p \end{aligned}$$

Radiative decays of hyperon states will provide unique information about the the 3-quark wave function in the presence of a strange quark. Since only the electromagnetic coupling is involved, the results can be interpreted directly in terms of the quark wave function: this is not the case in hadronic production, where distortions due to the strong initial state interactions are present. Several of the radiative transitions shown in Figure 7 will be measured.

Experiment 89-43 will measure the electroproduction of low mass hyperon states and also study the structure of the $f_0(975)$ meson in $ep \rightarrow epK^+K^-$. This state does not fit into the $q\bar{q}$ scheme of regular mesons, and is suspected to be either a weakly bound $(q\bar{q}) - (q\bar{q})$ molecule, or an exotic $(q\bar{q}q\bar{q})$ state. Information about the structure of this state is important for our understanding of the range of validity the non-relativistic quark model.

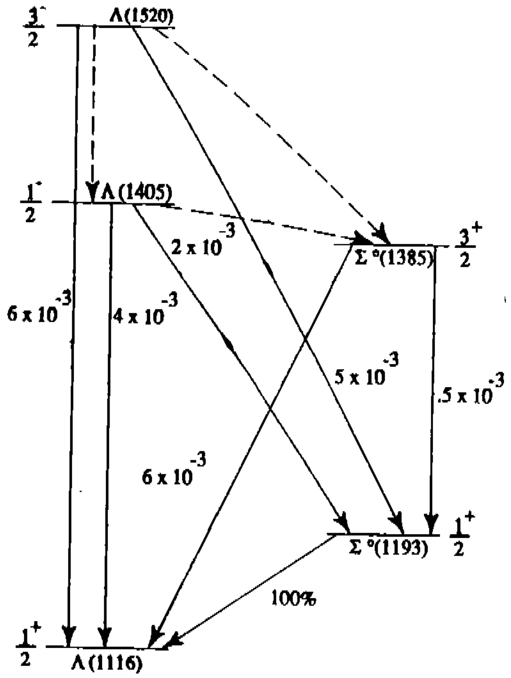

Figure 7: Radiative transitions of low mass hyperons with quark model predictions for transition probabilities.

Strangeness production on deuterium and heavier nuclei

In a nuclear system, the hyperon may be viewed as a controlled impurity which is unrestricted by the Pauli principle. It also lives long enough to sample the nuclear interior. These properties are used in the field of hypernuclear physics. For the case of the deuterium, hyperon production can be used to study YN interaction. Experiment 89-45 will measure the processes $\gamma D \rightarrow K^+(\Lambda n)$, and $\gamma D \rightarrow K^+(\Sigma n)$. The cross section for this process is expected to be strongly enhanced over the quasi-free production mechanism. The interference structure due to $\Lambda N \rightarrow \Sigma N$ allows to determine the relative sign of the amplitudes. As the photon energy crosses the $N\Sigma$ threshold a sharp structure is predicted to emerge. In the vinicity of this "cusp", two S = -1 dibaryons are predicted to occur. The lower mass D_0 is predicted to be narrow, and may show up in the missing mass plot of $\gamma D \rightarrow K^+X$ (Figure 8). Note that this state cannot be produced in (K, π) or (π, K) reactions.

A survey of strangeness production processes in heavier nuclei will be carried by experiment 91-14. Global information about the production of hypernuclear states will be obtained in these measurements.

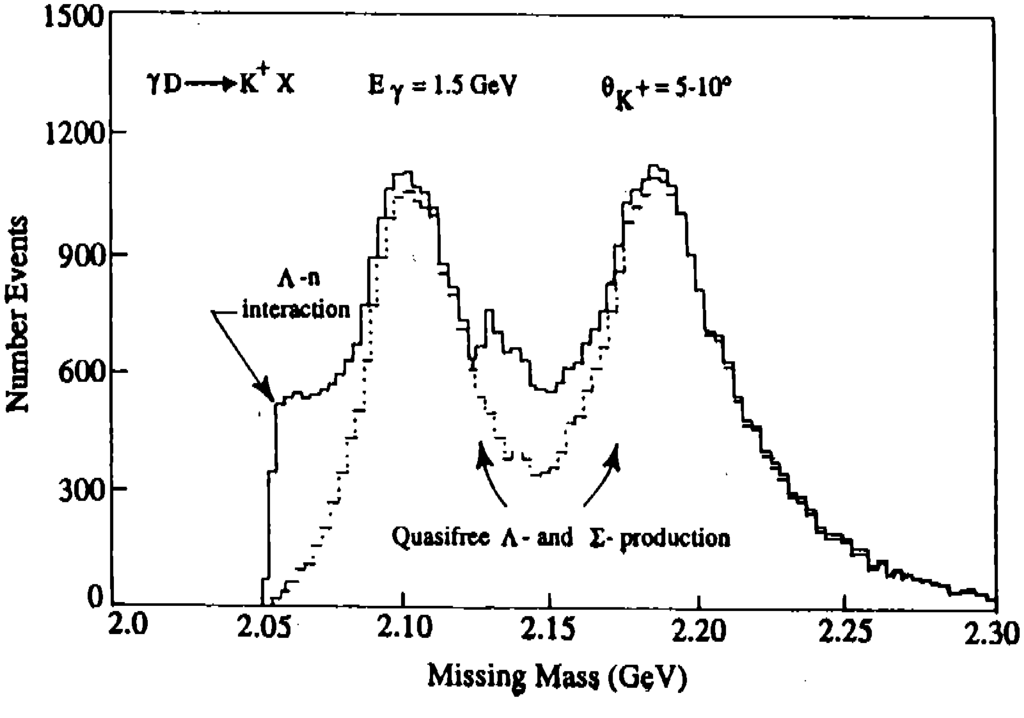

Figure 8: Monte Carlo simulation of $\gamma D \rightarrow K^+X$ for CLAS experiment 89-45.

V. Production of Multihadrons from Light Nuclei

Electron scattering on nuclei have concentrated on the electromagnetic structure of the ground state, and the excited states of nuclei in experiments where only the scattered electron was detected, and on measurements of nucleon single particle structure in $(e, e'p)$ processes where one additional proton is measured in coincidence with the electron. There are clear indications from these experiments at intermediate energies that multinucleon knockout processes are present in the quasi-elastic (QE), "dip", and $\Delta(1232)$ regions. In the QE region, the transverse response function measured in the $(e, e'p)$ reaction shows enhancement over the longitudinal response beginning at the two-body knockout threshold. In the dip region, the underestimation of the inclusive cross section by the theoretical calculations is a long-standing problem (Figure 9). The $(e, e'p)$ cross section in the dip and $\Delta(1232)$ regions show the contributions of multinucleon absorption processes.

The systematic study of the multinucleon absorption of the virtual photon is one of the goals of the CLAS multihadron experiments 89-15, -17, -27, -31, -32, and -36. Other goals include studies regarding the nature of short range correlations, high momentum components in the nuclear wave function, the origin of 3-body forces, and the production and propagation of nucleon resonances in the nuclear medium. All of these measurements require the detection of two or more hadrons in the final state in addition to the scattered electron. They can only be carried out using the full acceptance of CLAS.

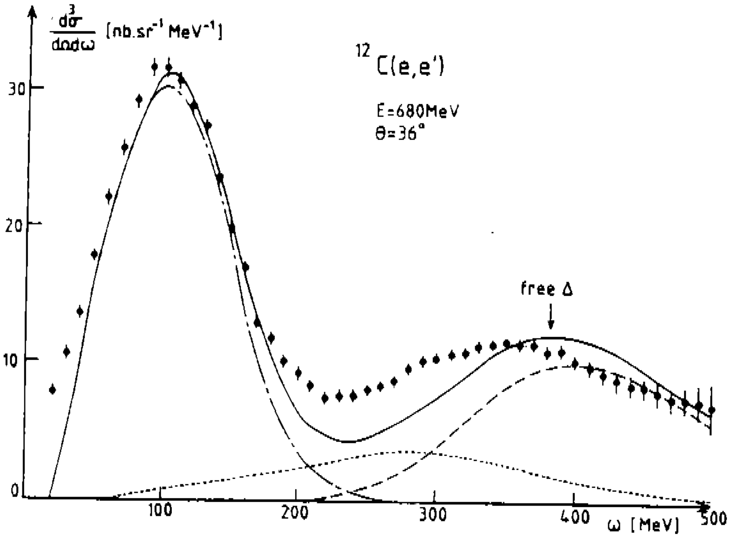

Figure 9: Inclusive electron scattering on ^{12}C

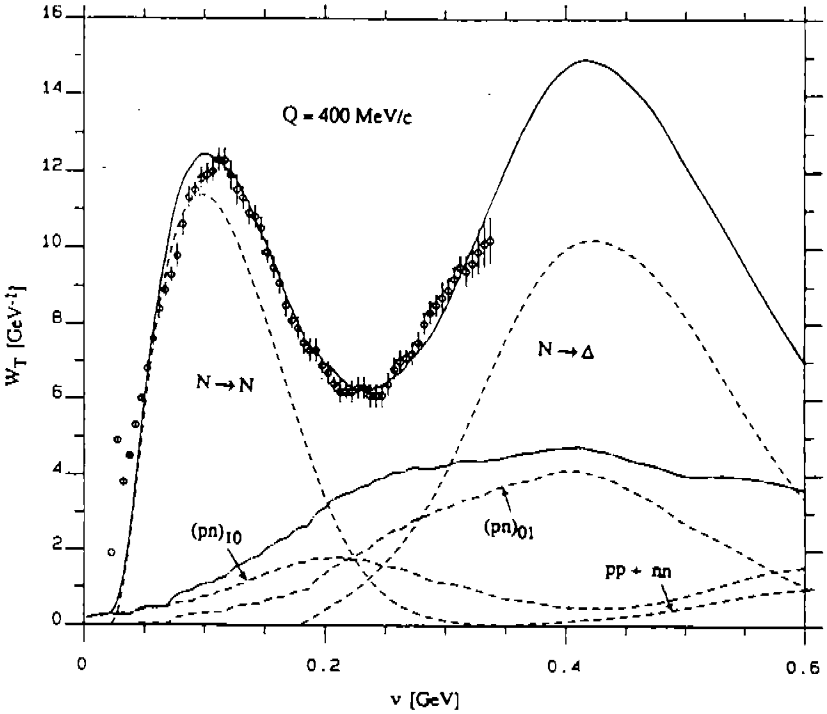

Figure 10: Transverse structure function of ^{12}C at $q = 450 MeV/c$. Dot-dashed line: total contribution of photon absorption on 6-quark clusters

The experiments will focus on the study of light nuclei where corrections due to final state interactions are relatively small and the interpretation is least ambiguous. ^3He and ^4He are the simplest nuclei for the study of initial state short range correlations. Theoretical calculations show that initial state nucleon-nucleon correlations in ^3He will result in enhanced longitudinal cross sections for two high momentum protons in the final state.

A possible explanation for the enhanced inclusive cross section in the dip region is contributions of multi-quark clusters to the nuclear wave fuction (Figure 10). Contributions of this nature may be studied in processes where the momentum of a fast forward going nucleon is approximately balanced by another backward going nucleon or by a Δ resonance. Since these objects are expected to be considerably smaller in size than the nucleus, their contributions are expected to become more important with increasing four-momentum transfer Q^2.

In the Δ region, inclusive (e, e') experiments show a systematic shift of the position of the Δ peak (Figure 11). For Fe, for example, the Δ position is shifted to 1175 MeV. This effect is theoretically not understood. Exclusive measurements of the type $(e, e'p\pi)$ allow reconstruction of the Δ mass from the final state hadrons. This will allow more detailed studies to be carried out, and shed new light on this problem.

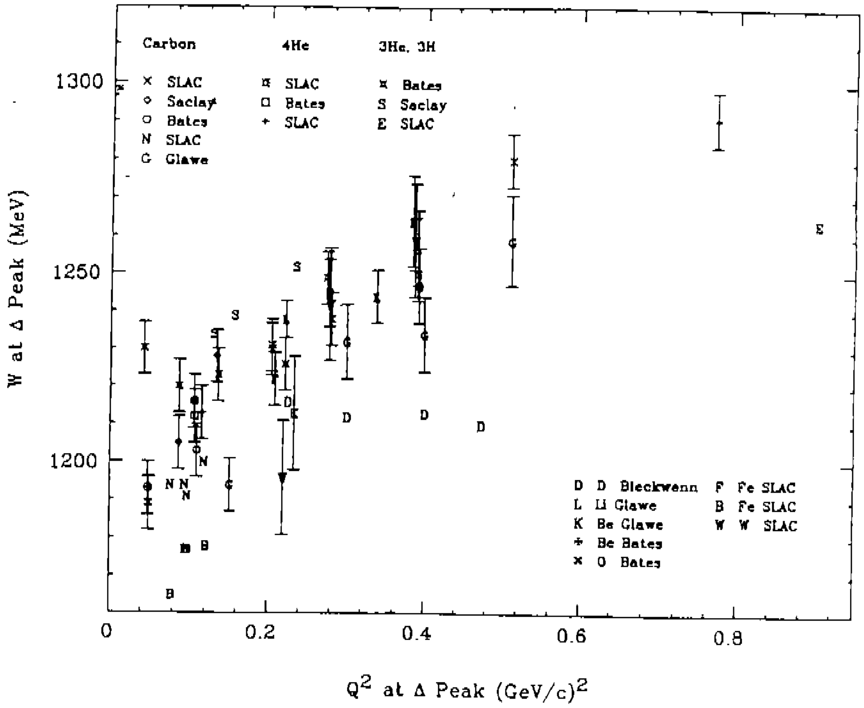

Figure 11: The mass shift of the Δ for various nuclei.

Three body forces are expected to enhance the cross section at kinematics where the final state momentum is shared approximately equally among three nucleons. One such configuration, usually referred to as the star configuration, occurs when the nucleons are ejected at equal momentum with a 120° angle between them in their center of momentum system. At high momentum transfers such configurations may be sensitive to short range three body forces resulting from the three gluon vertex in QCD. Evidence for such contributions may be found by carefully analyzing deviations of high momentum transfer processes involving three nucleons from predictions of conventional nuclear theory.